Classification of young stellar objects by CCD's and SED's

Authors: Paula Navarro Palomas
Advisor: Maria Rosario Isabel López Hermoso
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Catalonia, Spain.[*]

Abstract: The purpose of this study was to classify 19 Infrared Astronomical Satellite (IRAS) sources located in Cepheus molecular cloud. We have taken these sources because all have an CO outflow emission, which is an important tracer of star-formation process. We have obtained the flux of these protostars from the IRAS, Spitzer, WISE and 2MASS catalogs at far, medium and near infrared wavelenghts (FIR, MIR, NIR) to compute: color-color diagrams (CCD's) according to determine the evolutionary Class at which the IRAS sources belong to, and the spectral distribution of energy (SED) with the aim of check and complete the previous classification. We found 13 sources belonging to Class 0, 3 to Class I, 3 to Class 0/I and none of Class II and III.

I. INTRODUCTION

Young Stellar Objects (YSOs) are protostars embedded the densest regions of the interstellar medium, molecular clouds. The molecular cloud begins to collapse forming the dense nucleus of the protostar with a faint disk embedded in a dust envelope, i.e, produces a protostar during its free-fall phase. They emit part of its radiation at longer wavelengths causing excess infrared emission (IR), not in optical range due to the fact that are inside the dust and gas of the molecular cloud. Then, an intense wind phase ends the free-fall to reveal a newborn star surrounded by circumstellar disk. After the disappearance of the disk, we obtain an isolated star in the pre-MS that contracts in the HR diagram along the Hayashi track. It begins the main-sequence by the combustion of the hydrogen inside its nucleous. They can be observed from the detection of various tracers: molecular flows, masers, optical, infrared and continuous radius jets, Herbig-Haro objects and eruptions FU Orionis.

Protostars are not easily observed directly, that's why scientists established a criteria to know in which evolutionary phase the YSO is found. Two of these criteria are: the SED, which represents the distribution of energy by plotting the energy depending on its frequency, and the CCD's, which classifies the sources depending on their infrared excesses.

On the one hand, SED allows to have an idea in which evolutionary phase is the protostar and classify it to know if is more or less young. For plot the SED we need the flux density of the source and the wavelength at which it is measured. According to Lada et. al. [2], to classify the sources based on the shape of the observed energy distribution, we need to define the spectral index α as the slope of the SED.

$$\alpha = \frac{dlog(\lambda F_{\lambda})}{dlog(\lambda)} \tag{1}$$

In agreement with Lada et. al. [2] and the subsequent aggregation of Class 0 by André et. al. [3], we can classify the low mass YSOs in four classes based on the values of intervals of spectral index α (1).

Class 0: They have a similar SED of a black body at a single and very low temperature. They are the younger known objects. We can observe the envelope, formed by cold dust. André et al. [3] discovered this class, which emits strongly on the sub-milimeter range. They also can be detected by bipolar molecular flows or by continuous radio emission. Class I: Characterized by positive interval of spectral index: $0 < \alpha \leq 3$. They are the very young objects and very deeply embedded. This class is detectable in the NIR and sub-milimeter range. Class II: Characterized by negative or zero interval of spectral index: $-2 < \alpha \leq 0$. Pre-main sequence stars: T Tauri and those which present episodes FU Orionis, belong to this class. They have less circumstellar dust than Class I, therefore can be detectable in visible range besides IR. Class III: Characterized by very negative interval of spectral index: $-3 < \alpha \leq -2$. They are the most evolved objects. To this class belong the initial main sequence stars and the pre-main sequence stars called "naked" T Tauri stars. They almost do not have circumstellar dust, consequently can be detectable in visible range and have very little or no excess emission in NIR or MIR.

For high mass YSO there is no equivalent classification, because their formation takes place much faster and therefore, observationally, the evolution is more problematic to follow. They suffer severe damage on their surroundings once they begin to acquire large luminosities and usually reach the main sequence without loosing their envelope.

On the other hand, CCDs will enable us to classify the sources by their infrared excesses depending on their position, using different data in NIR, MIR and FIR bands.

In next section (II) We will explain the processing of the data of the 19 sources taken from [1]. Then, in section III, we will present the data processing results with a short discussion by showing two SED's and the different CCD's IRAS and 2MASS, including tables with a summarized information about the results. In section IV we will recapitulate the results.

[*]Electronic address: paula.navarrop@gmail.com

II. EXPERIMENTAL PROCEDURE

First of all, we collected different data of the 19 sources from different catalogs: IRAS, Spitzer, WISE and 2MASS. These data allowed us classify the sources by CCD's and SED's. IRAS sources are associated to PMS stars or protostars, i.e., young stellar objects. We have chosen these 19 objects because they are tagged as IRAS, which means they have infrared excesses and therefore they are very young.

We collected the most relevant magnitudes: the right ascension, the declination, the flux density or the magnitude of the source (depending on the catalog) from the website [4].

Firstly, once at [4], we selected the *finder chat* icon in order to obtain how the source looks in different bands. Secondly, we select Single Object Search and we wrote the coordinates of our object. The size of the field is by default 300s, therefore, if there was more than one source, we would reduce the field at not less than 60s, to find the most probable source, i.e., best match in its position. After that, we selected the catalogs that interested us with the aim of collect the information about the physical magnitudes mentioned before. In case of IRAS data, we also collected the information of the semimajor, semiminor and position angle of the error ellipse, since the accuracy in the position of the sources in the IRAS catalog is lower than others, so it may happen that within the error ellipse there is more than one source in contrast to the other more accurate catalogs that have been consulted. We proceeded to repeat these steps for all the catalogs mentioned before.

For IRAS catalog we wrote a table with all magnitudes specified above. It gave us the flux densities at 12, 25, 60 and 100μm since IRAS satellite works at these wavelengths, i.e., MIR and FIR. Spitzer catalog provide us the flux densities at 3.6, 4.5, 5.8 and 8μm, i.e., NIR and MIR bands. But we had a drawback, we only found information about three of them. Due to this, we used WISE catalog, which provide us the flux densities at 3.4, 4.6, 12 and 22μm, to find data from two fisrt bands since they are very similar to those of Spitzer. With 2MASS catalog, we obtained the flux density of the sources at 1.2, 1.6 and 2.2μm which are wavelengths of NIR.

At this point, with all the magnitudes and flux densities obtained from different catalogs, we plot a CCD's in order to classify, as far as possible, the 19 sources. We additionally represent the SED of each source, using the different flux densities and its corresponding wavelengths, for the purpose of assigning to which class they belong, i.e., their evolutionary stage, according to their spectral index.

Finally, we also looked for other evidences of star formation, besides the CO outflow, as masers, optical, infrared and continuous radius jets, emission on the submilimeter range and HII regions, i.e., ionized regions by a young and sufficiently hot star which emits over a large range of wavelengths, from the UV to the radio range. To do so, we visited the SIMBAD Astronomical Database - CDS website [5] and searched for the reference articles that could give us relevant information about each IRAS.

III. RESULTS AND DISCUSSION

A. IRAS CCD

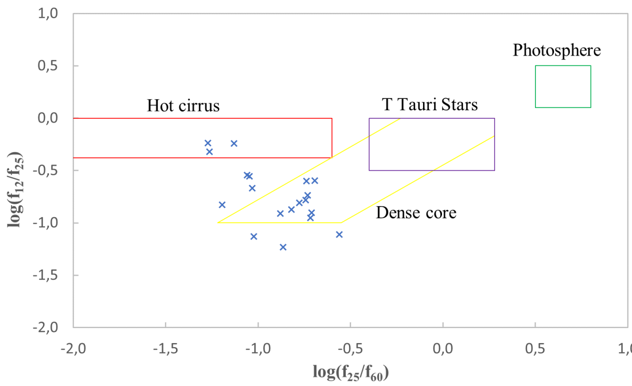

Figure 1: CCD based on the IRAS flux densities at 12, 25, 60 and 100μm. The boxes represented are from Beichman [6].

According to Fig.1 we are able to classify the sources, taking into account the equivalences with the different classes:

Box	Class	Sources	Percent (%)
Dense core	0	9	47,4
Hot cirrus	I	3	15,8
T-Tauri stars	II	0	0
Photosphere	III	0	0
No assignment		7	36,8

Table I: Classification of the sources from Fig.1 according to their class.

Analysing Tab.I and Fig.1 we can see that most of the sources (63,2%) belong to Class 0 and I while the others are not assigned to any Class. The sources belonging to Class 0/I, are very young objects, probably low-mass protostars, that have not yet evolved very much. Their ages are between 10^4 and 10^5 years old. These sources are located in the dense core and hot cirrus region.

On the other hand, we have not found any source classifiable as Class II and Class III. This means that there is any source found in PMS or at the beginning of the MS. Therefore, the IRAS we have studied are not in an advanced evolutionary stage.

Accordingly, by analyzing the flux densities of the different wavelengths provided by IRAS, i.e. the fluxes in the mid and far infrared ranges, we can conclude that in this region of space there are young stellar objects in their early evolutionary stages.

B. 2MASS CCD

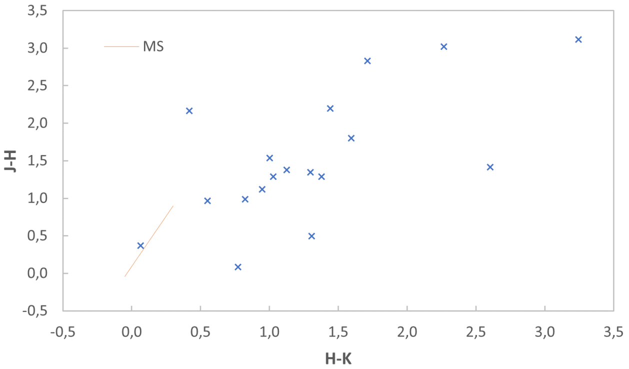

Figure 2: CCD of the 2MASS using the 3 bands J(1.2μm), H(1.6μm) and K(2.2μm) of the NIR, plotting the values of the J-H and H-K magnitudes.

The younger the sources are, the more material there is around them and therefore, the more extinction. We should remember that the extinction in the optical range and at short wavelengths is very high, so it is necessary to observe at long wavelengths, i.e., in the FIR, to be able to study the source well, since in that range the extinction is not very important. As it affects mostly at short wavelengths, it agrees with what we see in Fig.2, since all sources are reddened because at 1., 1.6 and 2.2μm, blue light suffers more extinction than red light.

We can also see that the sources are not in the MS trade as expected. The only source that comes close to it is IRAS 23250+5837, it could be because in the region where the YSO is located, there are 3 sources that could influence the flux data in such a way that the source looks less reddened than it really would be.

C. Spectral Energy Distributions

In Fig.3 we have selected and represented the spectral energy distribution of two of the 19 sources studied. Taking a look, we can see that they both have a positive slope, therefore, we can advance that they will belong to Class 0/I. Specifically, applying Eq.1 on both sources we obtain $\alpha = 1.14$ for IRAS 22539+5758, and a slightly higher spectral index $\alpha = 1.88$ for IRAS 23138+5945. As we have already pointed out, they belong to Class I/0. In order to distinguish Class I from Class 0 we have used two methods.

On the one hand, we have applied the criterion of P. S. Teixeira et. al. [7], where α_W is defined as in Eq.1 but only using the WISE wavelengths. Class 0 corresponds to $\alpha_W > 0.3$ and Class I to $0.3 \leq \alpha_W < -1.8$. For source IRAS 22539+5758, using the WISE fluxes and their corresponding wavelengths, we have obtained a $\alpha_W = 2.33$, therefore belongs to Class 0.

On the other hand, the remaining source ambiguity can be eliminated by using the criterion of Fig.1. Since IRAS 23138+5945 is located in the dense core region, we can state that it belongs to Class 0.

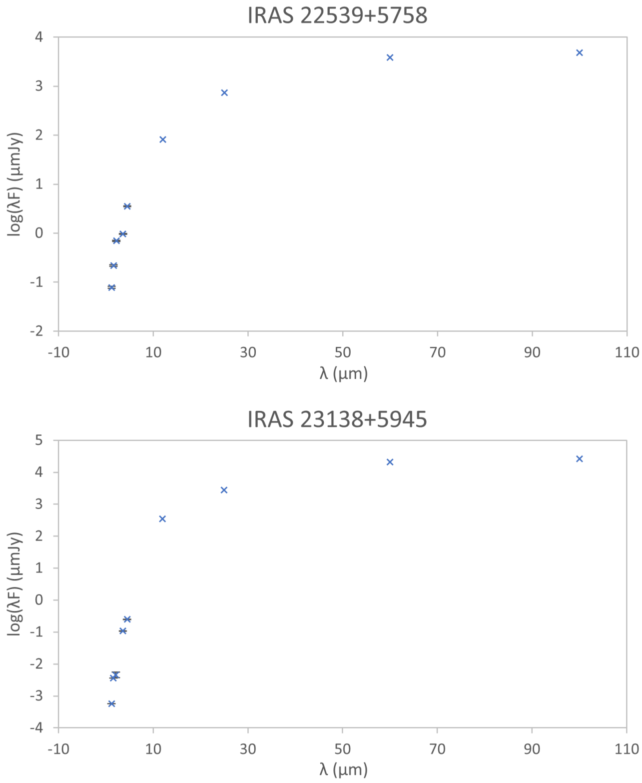

Figure 3: SED's from IRAS 22539+5758 and IRAS 23138+5945 sources. The first one is plotted with WISE data and the second one with Spitzer data.

In this section, we have only given the spectral index values of two sources. In appendix we can find the 19 sources with their respective: spectral index, following the Lada and WISE criteria, classification, depending on the applied criterion, and the associated tracers. We can summarize all the information as follows:

Class	Sources	Percent (%)
0	13	68,4
I	3	15,8
0/I	3	15,8
II	0	0,0
III	0	0,0

Table II: Classification of sources according to CCD's and their respective spectral indices considering the criteria discussed above.

We can verify that the criteria do not contradict each other at any time, i.e., if a source belongs to Class 0 according to one criterion, the other is either not able to classify the source or they match in the classification.

Taking into account all the information that we have discussed in the paper, summarized in Table II, we can conclude that the 19 sources are between their first two evolutionary stages, i.e., they are very young objects, between 10^4 and 10^5 years old, in the process of formation by the continuous accretion of material from the molecular cloud in which they are embedded.

IV. CONCLUSIONS

- In the IRAS CCD, we have obtained 9 Class 0 sources, 3 Class I sources and 7 unclassified.
- In the 2MASS CCD, we have noticed that all sources are reddened.
- In the SED's, we have obtained 13 Class 0 sources, 3 Class I sources and 3 Class 0/I sources.
- We have found tracers of star formation in all sources.

Acknowledgments

First of all, I would like to give special thanks to my parents for all the support they have given me during all these years, for believing in my potential and encouraging me to go ahead. I would also like to thank Rosario to take my final project and above all, for the help and involvement she has given me during these difficult times. Finally, I would like to mention my friends and family for the moral support they have given me since the beginning.

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[4] `https://irsa.ipac.caltech.edu/frontpage/`
[5] `http://simbad.u-strasbg.fr/simbad/`
[6] Beichman C.A., *Light on Dark Matter*, ed. F. P. Israel (Dordrecht: Reidel), **279** (1985)
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Appendix

Source	α [h ' "]	δ [h ' "]	α	α_W	*Class*	$Class_{WISE}$	$Class_{IRAS}$	Tracers[a]
IRAS 22475+5939	22 49 29,0	59 54 56	1,46	0,98	Class 0/I	Class 0	Class 0	HII, IR
IRAS 22506+5944	22 52 38,1	60 01 01	1,49	1,05	Class 0/I	Class 0	Class 0	HII, IR, MH
IRAS 22528+5936	22 54 49,6	59 52 47	1,10	0,60	Class 0/I	Class 0	Class 0	IR, smm, MH
IRAS 22539+5758	22 55 59,8	58 14 42	1,14	2,33	Class 0/I	Class 0	Class 0	IR, HII, MH
IRAS 22542+5815	22 56 17,0	58 31 13	1,68		Class 0/I		NC	IR
IRAS 22566+5830	22 58 42,6	58 47 45	1,81		Class 0/I		NC	IR, HII, MH
IRAS 22570+5912	22 59 05,5	59 28 23	1,23		Class 0/I		Class 0	IR, HII
IRAS 23011+6126	23 03 12,8	61 42 25	0,84	4,85	Class 0/I	Class 0	NC	IR, HII, smm, MH
IRAS 23030+5958	23 05 09,9	60 14 31	1,68		Class 0/I		Class 0	IR, HII
IRAS 23032+5937	23 05 23,1	59 53 53	1,39		Class 0/I		NC	HII, MH, smm
IRAS 23033+5951	23 05 25,2	60 08 15	1,28	3,38	Class 0/I	Class 0	Class 0	HII, MH, MM, smm
IRAS 23037+6213	23 05 48,9	62 30 01	1,06		Class 0/I		Class I	IR, MH
IRAS 23133+6050	23 15 31,3	61 07 10	1,41	0,87	Class 0/I	Class 0	NC	IR, HII, smm
IRAS 23138+5945	23 16 04,8	60 02 00	1,88		Class 0/I		Class 0	HII
IRAS 23139+5939	23 16 10,4	59 55 28	1,67	5,73	Class 0/I	Class 0	NC	HII, smm, MH
IRAS 23140+6121	23 16 11,7	61 37 45	1,40		Class 0/I		NC	IR
IRAS 23146+5954	23 16 48,9	60 10 46	1,69		Class 0/I		Class I	IR
IRAS 23151+5912	23 17 21,0	59 28 49	1,39	4,72	Class 0/I	Class 0	Class 0	IR, HII, smm, MH
IRAS 23250+5837	23 27 18,5	58 54 44	1,29		Class 0/I		Class I	IR, MH

[a] They all have outflow of CO_2

Table III: Classification of YSO's. From left to right: α: spectral index defined in Lada et. al. [2]; α_W: WISE spectral index defined in F.S. Teixeira et. al. [7]; Class: classification of sources according to α; Class$_{WISE}$: classification of sources according to α_W; Class$_{IRAS}$: classification of sources according to Fig.1. Tracers: HII: HII regions, MH: masers of H_2O, IR: infrared source, smm: sub-millimetric source.